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ANALYTICAL AND EXPERIMENTAL STUDY ON PDC DRILL BITS QUALITY

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1 INTRODUCTION

The main technologies used in rock drilling industry are roller cone and drag bits. On one hand, roller cone bits work by impact excavation mode and they are currently used in hard rock formations where they show a convenient wear resistance. On the other hand, drag bits operate in softer rock formations because of an efficient shearing mode but display a lower wear resistance. Because excavation rate is directly related to the overall cost, PDC cutters shearing work is really attractive comparing to roller cone drill bits. Actually, PDC bits could drill twice faster and longer than roller bits even in hard formations [1]. Thereby, the petroleum and hydrothermal investigation in deep geological formations, characterized by confined pressure greater than 120 MPa, leads to manufacture a new kind of bits materials able to drill at higher temperature, in more abrasive and harder geological fields.

Innovating materials, sintering process and design recently developed to improve drill bits hardness and fracture toughness also require in parallel a new strategy in quality measurement. According to the destructive mode of drag bits, quality can be defined by two important parameters: materials wear rates and excavation performances. In the case of measuring wear rates, the well-known Archard's model has been successfully used in several works to describe PDC/rock sliding contact behavior [2]. The cutting efficiency evolution is closely linked to the wear flat formation during friction and is initially determined by the PDC active area (i.e. depth of cut). The aim of this paper is to propose a quality criterion Q for a given PDC cutter which gathers different parameters already used in drilling mechanism analysis.

2 EXPERIMENTAL STUDY

The weight and torque on bit, defined for an optimal penetration speed, could be considered as independent of the number of bits [3]. However, a correct cutter repartition is required to insure a homogenized wear on them [4]. Therefore, wear behavior and drilling performance information based on single cutter experiments are relevant and can be extrapolate for understanding of the whole tool mechanism.

A vertical lathe-type device enables coherent wear mechanism simulation with actual drilling action. Cutters, brazed on sample holders, were adjusted downward on the lathe shaft. Rings forming rock counter-faces are 1 m in external diameter, 0.5 m in internal diameter and 0.6 m thick.

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Experiments were carried out with some constant parameters coming from real drilling conditions (Figure 1): normal load range from 3000 to 5000 N, back rake angle at 15°, depth of penetration at 2 mm and mean cutting speed around 1.8 $m \cdot s^{-1}$. Tests were made in atmospheric environment and no lubricant was added into the contact.

Ring-stones of same mortar composition were selected because of their basic manufacture and homogeneous mechanical properties. In order to create significant wear on samples, several grindstone rings were necessary. Experiments are performed in four sequences for one mortar ring and each sequence represents three radial round-trips (i.e. an excavation length about 510 m). One grindstone is used for a total cutting and sliding length of 2040 m. Six to eight of them were used to cover around 15 km of experimental drilling process. At the end of every sequence, height of material lost is measured to calculate cross-sectional area of cut and cutter worn volume.

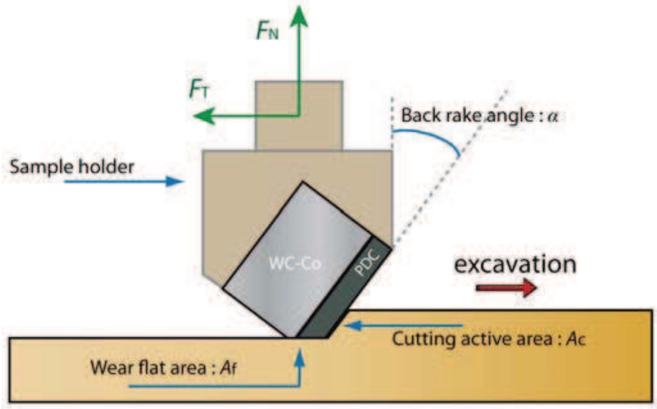


Figure 1. Schematics of cutter/rock interactions

A series of six cutters (C, F, G, H, I and J), from diverse manufacturers, were selected to represent a large range of physical behaviors. Cutters are made of a tungsten carbide cylinder surmounted by a diamond table. Material parts have a diameter of 13 mm, the tungsten carbide cylinder has a height of 8 mm and the diamond layer is 2 mm thick.

Each of these two materials has an amount of cobalt induced by the sintering process which is about 6%wt for the tungsten carbide part and 2%wt for the diamond one. Therefore, it is important to note that sample J and sample I have been exposed to a chemical post-treatment called "leaching process" [5] which removes the cobalt grain boundaries on the diamond layer over 200 µm deep for sample J and only 100 µm for sample I.

3 WEAR RATE ANALYSIS

Because this study is clearly a case of abrasive friction between cutter and hard rock sliding contact, Archard's model is an interesting choice. This model has been extensively involved in tribological studies because of its simple and correlative linear equation (6) between wear volume V_c and friction work i.e. the product of friction transversal stress component F_T^f or normal F_N^f by distance L (Figure 2). As related by Fairhurst and Lacabanne [6], cutting action and friction can be considered as independent (5) in the drilling procedure. Moreover, F_N^f can be approximated as the difference between normal stress on the cutter F_N and the initial value of F_N noted $F_N(0)$ (idem for transversal stresses F_T and F_T^f).

$$\begin{cases} F_N = F_N^f + F_N^c \approx F_N^f + F_N(0) \\ F_T = F_T^f + F_T^c \approx F_T^f + F_T(0) \end{cases} \qquad V_c = k \cdot F_N^f L \approx k \cdot [F_N - F_N(0)]L \tag{5, 6}$$

Several authors worked on the meaning of coefficient k by expressing it as a function of rock and cutter material hardness for example. But here, only proportionality is considered, and no identification is made on it.

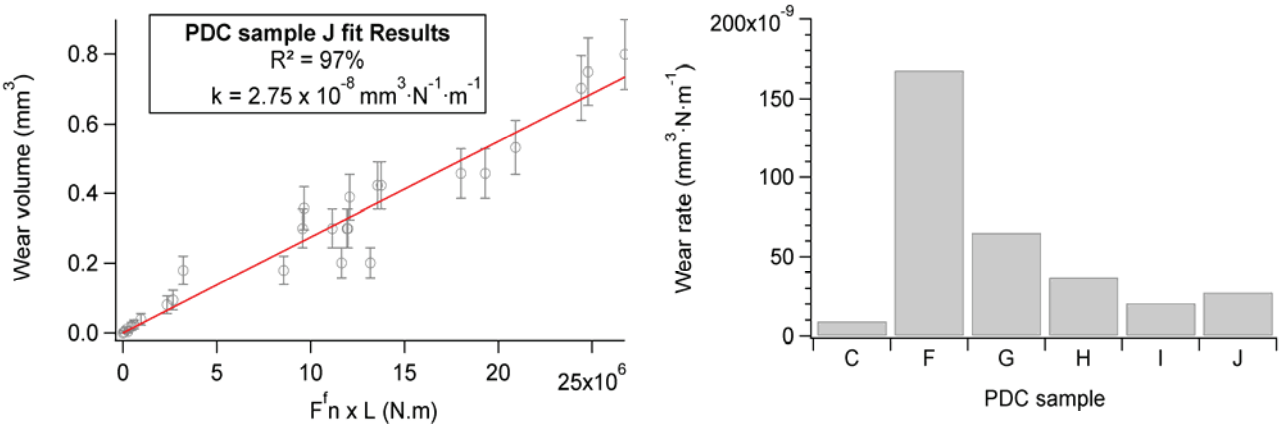


Figure 2. Archard's model applied to sample J and wear rates results

The lowest wear rate value was obtained with cutter C with less than $1{\cdot}10^{-8}$ mm^{3}N^{-1}m^{-1}. Cutter F was identified as the highest with a rate over $15{\cdot}10^{-8}$ mm^{3}N^{-1}m^{-1}.

4 CUTTING EFFICIENCY COEFFICIENT

As demonstrated by Detournay and Defourny [7], an affine equation (3) establishes a relation between torque on cutter (i.e. F_T) and weight on cutter (i.e. F_N). In this equation, constants ε, μ and ζ are respectively the intrinsic specific energy, the friction coefficient and the cutting coefficient.

Specific energy E represents the energy needed to cut a unitary rock volume. This energy results from mechanical efforts (i.e. the work W_m) and is equal to the working stress multiplied by the cutter travel distance. Tool front face lateral displacement implies that dug volume V_R is equal to the product active area A_c by distance L. Finally, transversal stress on the cutter F_T and A_c measurements permit specific energy calculations.

The ratio between ε and E characterizes the drilling process efficiency η (4). This efficiency represents the part of cutting in the overall mechanical action and pure cutting means that $\mu = 0$ then $E = \varepsilon \approx E_0$ (with E_0 the initial value of E).

$$E = \frac{W_m}{V_r} = \frac{F_T}{A_c} = \mu \frac{F_N}{A_c} + (1 - \mu\zeta)\varepsilon \qquad \eta = \frac{\varepsilon}{E} = \frac{E_0}{E} \tag{3, 4}$$

The decrease of efficiency η as a function of distance L is nonlinear. According to experiments, an interesting fitting curve has been identified for all cutters. At the excavation beginning, efficiency tends to 1 and when the distance L becomes greater (mathematically infinite), η tends to a critical value N_c. Accordingly, an empirical equation can be deducted from experimental data, and an exponential law seems adequate to evaluate relative efficiency behavior on a series of PDC samples.

Cutting efficiency is expressed (7) as a function of the excavating distance with constant values of N_o, N_c and the cutting efficiency coefficient u.

$$\eta = (N_0 - N_c) \cdot \exp(-\frac{1}{u} \cdot L) + N_c \tag{7}$$

N_o is used in cases in which η can reach values higher than 1, due to rock formation fluctuations or transitory periods occurring before cutting process stabilization.

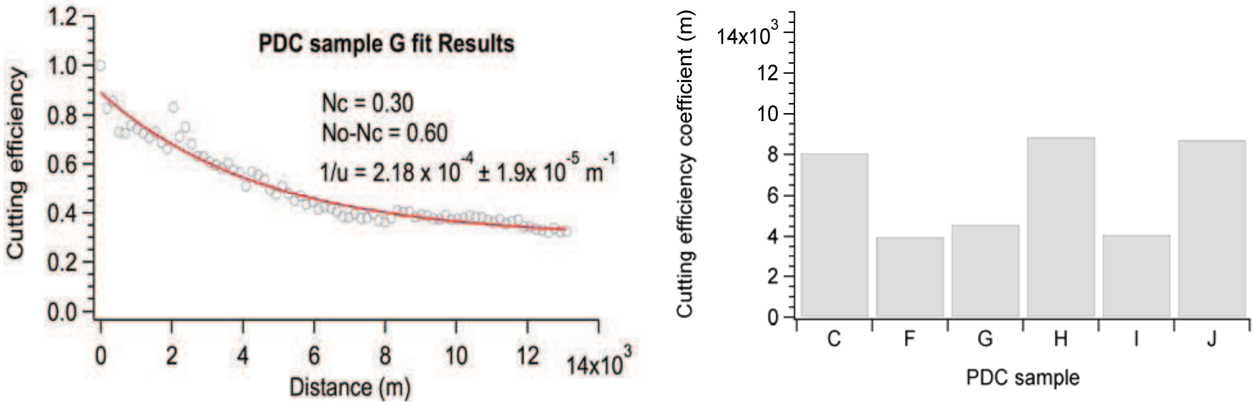


Figure 3. Cutting efficiency vs. distance model for sample G and cutting efficiency coefficients

Minimum values of the u coefficient were measured with F, G and I cutters around 4000 m and maximum coefficients were obtained with H and J over 8700 m.

5 QUALITY MODEL

Obviously, the only analysis of wear endurance or cutting efficiency doesn't permit to discriminate cutters relative quality of cutters. The grade assessment of PDC samples depends on its tribological behavior (i.e. here friction and wear), drilling efficiency and rock cutting resistance (i.e. intrinsic specific energy). A low wear rate and a high efficiency attest that the sample is a high quality cutter.

The grinding ratio G between rock wear volume V_r and cutter wear volume V_c is already used to estimate cutters resistance to abrasive wear [5]. Using previous equations, this ratio can be directly related to ε, μ, k and η (8).

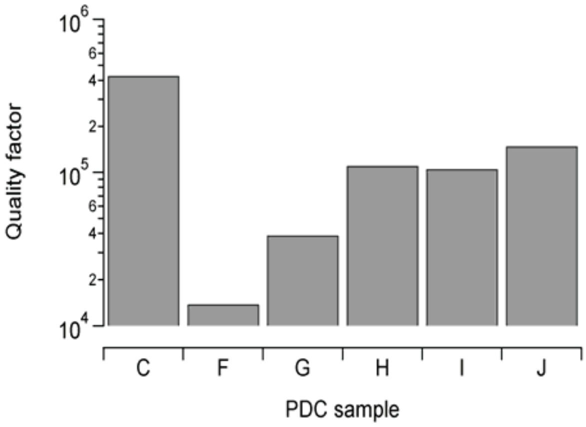
$$G = \frac{V_r}{V_c} = \frac{A_c L}{k \cdot F_N^f L} = \frac{\mu F_T^c}{\varepsilon k F_T^f} = \frac{\mu F_T^c}{\varepsilon k \left(F_T - F_T^c\right)} = \frac{\mu}{\varepsilon k}\left(\frac{F_T}{F_T(0)} - 1\right)^{-1} = \frac{\mu}{\varepsilon k}\left(\frac{1}{\eta} - 1\right)^{-1} \tag{8}$$

Then, it is interesting to define the quality factor Q, a constant value integrating all η variations on the total excavation distance L_T of the G ratio (9).

$$G \approx \frac{\mu}{\varepsilon k}\left(\frac{1}{\exp\left(-\frac{1}{u}L\right)} - 1\right)^{-1} = \frac{\mu}{\varepsilon k}\left(\exp\left(\frac{L}{u}\right) - 1\right)^{-1} \approx \frac{\mu}{\varepsilon k}\frac{u}{L} \quad \Rightarrow \quad Q = \frac{\mu}{\varepsilon \cdot L_T}\frac{u}{k} \tag{9}$$

This definition of quality takes into account coefficients μ, ε and L_T and permits to normalize and compare different cutters when they meet variations in rock mechanical properties or excavation distance between experiments. Then, the ratio u on k explains the compromise between cutting efficiency and wear in the quality formula.

Results display the interest in confronting parameters and evaluating a quality coefficient (Figure 4). Cutter C is clearly the best cutter with a Q factor about $43 \cdot 10^4$, which is confirmed by its low wear rate and its high cutting performance. On the opposite, the F cutter has the worst Q factor with $1 \cdot 10^4$.



Sample	μ	ε (MPa)	L_T (m)	k ($\times 10^{-9}$ $mm^3 \cdot N^{-1} \cdot m^{-1}$)	u (m)	Q ($\times 10^4$)
C	0.26	35	15130	9	8064	43
F	0.20	27	12580	168	3968	1
G	0.21	29	13090	65	4587	4
H	0.21	32	14110	37	8849	11
I	0.23	28	15130	21	4082	10
J	0.25	35	15130	27	8703	15

Figure 4. Quality factor calculated for samples C, F, G, H, I and J.

Samples have been also submitted to X-ray diffraction measurements to qualify relative differences between samples' diamond layer (Figure 5). In addition to diamond material, two other phases have been identified on diffractograms, which are tungsten carbide (WC) and cobalt carbide (CCo_4). WC phase is present on all the samples and only F, G and H possess CCo_4 XRD signature.

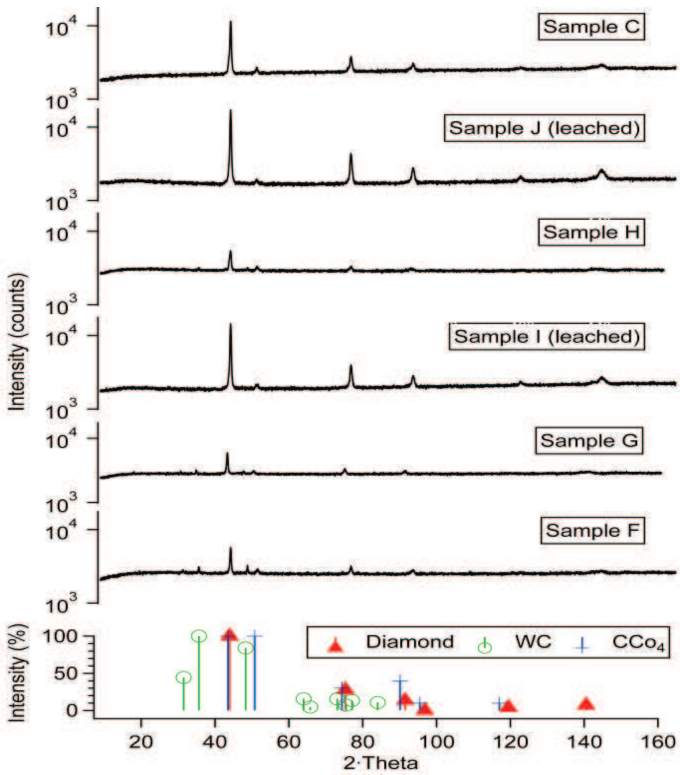


Figure 5. Diffractograms of PDC samples C, F, G, H, I and J classified from low Q (sample F) to high Q (sample C) and calculated stick pattern of diamond, tungsten carbide and cobalt carbide.

XRD peak intensity depends on the amount of the identified crystallized phase. After analyzing diffractograms, it is clear that quality is related to diamond purity and secondary phase concentrations. Moreover, it appears that for the lowest quality samples an additional cobalt carbide phase is detected.

Concerning leached PDC cutters, the high relative amount of diamond induced by the chemical procedure can be detected on diffractograms. However, the leaching is effective only on a thin layer representing only 5 % of the overall diamond. That should be the reason of the lower Q coefficient for sample I than sample H even if the first one seems to have a better diamond degree of purity phase.

6 CONCLUSION

PDC cutters were submitted to wear tests and a comparison between all these cutters requires an overlap of information. PDC cutters evaluation tends to balance ability to withstand abrasive wear and to be efficient as long as possible. For this purpose, quality concept is formulated to associate cutting efficiency and wear behavior of a cutter:

- Archard's linear model permits a correlation between wear volume and mechanical work in order to calculate wear rate. However, a long bit life could be related to a poor excavation performance.
- During tests, cutting efficiency curves on several samples show similar decreasing tendency. An exponential law properly associates cutting efficiency to excavating length and leads to determinate a cutting efficiency coefficient.
- Ratio between cutting efficiency coefficient and wear rate establishes a quality coefficient. In this paper, this approach, performed on six cutters, reveals an interesting quality rank.

Eventually, diffractograms permit to correlate the quality coefficient to the amount of diamond in PDC samples compared to tungsten carbide and cobalt carbide crystallized phases.

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